**Final Report**

# Fluid-Optic Interactions

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**AFOSR Grant F49620-93-0163**


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This report describes fluid-optic interaction research at the University of Notre Dame. This research has been extremely productive in both developing a new, high-bandwidth (100 KHz), time-resolved wavefront sensor and in terms of producing new information about the nature of the effect on an optical signal's wavefront of propagation through a turbulent, optically-active flowfield. During the course of the research, a numerical point-vortex method for simulating shear flows was developed and played a crucial role in developing the new wavefront sensor and interpreting the results of wavefront time series obtained by using the sensor to investigate optical propagation through low-speed jets and high-speed shear layers. Wavefronts were collected for propagation through a two-dimensional heated jet; the heated-jet facility was developed specifically for this research. The spatial and temporal frequency content of these wavefronts was extensively analyzed leading to a new understanding of the nature of Aero-Optical phenomena. Further, the heated-jet wavefronts were used to study the problems involved in attempting to correct Aero-Optically distorted wavefronts using adaptive-optic techniques. The new sensor was also used to collect optical wavefronts due to propagation through a Mach 0.8 compressible shear layer similar to those that are encountered in aircraft flight conditions.

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## Executive Summary

This report covers the activities at the University of Notre Dame under AFOSR Grant F49620-93-0163, "Fluid-Optic Interactions." The report begins with a discussion of the relevance of the research to Air Force missions and places the work in context with work performed in this field prior to the time the grant effort was begun. This research effort has been extremely productive in both developing a new, high-bandwidth (100 KHz), time-resolved wavefront sensor and in terms of producing new information about the nature of the effect on an optical signal's wavefront of propagation through a turbulent, optically-active flowfield. During the course of the research, a numerical point-vortex method for simulating shear flows was developed and played a crucial role in developing the new wavefront sensor and interpreting the results of wavefront time series obtained by using the sensor to investigate optical propagation through low-speed jets and high-speed shear layers. Wavefronts were collected for propagation through a two-dimensional heated jet; the heated-jet facility was developed specifically for this research. The spatial and temporal frequency content of these wavefronts was extensively analyzed leading to a new understanding of the nature of Aero-Optical phenomena. Further, the heated-jet wavefronts were used to study the problems involved in attempting to correct Aero-Optically distorted wavefronts using adaptive-optic techniques. The new sensor was also used to collect optical wavefronts due to propagation through a Mach 0.8 compressible shear layer similar to those that are encountered in aircraft flight conditions. The results of the research were communicated directly to Air Force personnel working in the technical area at the Air Force's Phillips Laboratory, and several technology transfers took place. The research results were also presented at many national technical meetings. The work is documented in a Master Thesis and a Ph.D. Dissertation, eight meeting papers and four journal articles.

CONTENTS

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## I. Introduction

The use of optical signals propagated through fluids is ubiquitous in Air Force and DoD applications. These applications include, but are not limited to, imaging distant objects from ground-based and airborne systems, tracking, communication, ranging, sensing incoming threats, irradiating targets for weapons-delivery identification, and destroying targets by irradiation with high-power lasers. Most of the applications depend to one extent or another on the wavefront of the associated optical signal maintaining its "figure." Aberrations (distortions of figure) on optical wavefronts degrade the ability of an optical system to image, focus, or otherwise use the optical signal associated with the propagating wavefront for the system's intended purpose. When an otherwise planar (flat-figured) optical wavefront propagates through an optically-active field (i.e., a field of variable index of refraction), the wavefront emerges aberrated. If the imposed aberrations are known and constant, measures may be taken to compensate for the aberrations to improve the

performance of the optical system; however, when the aberrating field is rapidly time varying the problem of compensation becomes more complicated. Because in the case of a Fluid-Optic interaction, the distortion is caused by the dynamically-changing turbulent flowfield, the wavefront's aberrations are themselves dynamically changing. Although the spatial and temporal frequencies of the optical aberrations are related to the spatial and temporal character of the turbulent flowfield, the optical aberrations result from an integrated path through the variant-index field associated with, but not identical to the turbulent flowfield, and, as such, cannot be directly related to any particular instantaneous spatial feature in the flowfield; however, the fact that the aberrations are associated with features in the turbulent flowfield, features which convect at some velocity in the flow direction, means that the aberrated features on the wavefront "convect" in the flow direction, and this fact has been of critical importance to our research.

Prior to the initiation of the present research, only approximate methods existed for estimating the time-averaged spatial optical degradation due to propagation through shear and boundary layers; these estimates were in the form of an rms Optical Path Difference (OPD). State-of-the-art wavefront sensors at the time we began our grant research were capable of sensing the instant-to-instant wavefront figure at rates of approximately 1 - 2 kHz. As will be discussed below, for Air Force applications, rates of one to two orders of magnitude higher are required to investigate the detailed dynamics of turbulent-flow-induced wavefront aberrations. Thus, for most applications of interest to the Air Force, prior to our research essentially no methods were available for even estimating the spatial and temporal character of the dynamic wavefront aberrations.

## A. Categorization of Fluid-Optic Interactions

Fluid-optic-interaction problems have been historically divided into two categories: *Atmospheric Propagation* and *Aero-Optics*. The first category is associated with propagation of light through aberrating fluids over extended distances, where the pathlength of the propagation is long compared to the viewing aperture. Because this category was initially associated with viewing of celestial objects through the atmosphere, it has come to be known as "Atmospheric Propagation." The spatial and temporal frequencies associated with Atmospheric Propagation can be relatively low, as will be discussed below. The second category is associated with aberrations imprinted on the optical wave due to relatively short propagation distances compared to the viewing aperture. This second category has emerged as an area of investigative interest over the last three decades and is generally associated with optical propagation through relatively-thin boundary layers and shear layers found in flows around airplanes; this explains the origin of the term "Aero-Optics." The spatial and temporal frequencies associated with Aero-Optics can be many orders of magnitude greater than those associated with Atmospheric Propagation.

## B. Levels of Understanding

There are four levels of understanding associated with the fluid-optic-interaction problem which may be generally arranged in their order of complexity as follows: first, there is the level of understanding that allows one to estimate the statistical degree of optical distortion that is likely to be encountered for a particular optical-propagation scenario through a flowfield. The second level is to be able to predict, not only the

statistically-averaged distortion, but the spatial and temporal frequencies associated with the time-varying optical distortion. The third level is to be able to measure the actual time histories associated with the optical distortions and link such histories to specific fluid-mechanic character of the flowfield. The fourth level is to be able to measure the optical distortions in "real time" so as to improve/restore the optimal performance of the optical system.

## C. Background

A review of previous work addressing the various levels of understanding of the fluid-optic interaction problem is contained in Appendix A. Suffice it to say here that an extensive body of work exists on all four levels of understanding in the case of Atmospheric Propagation. At the fourth level, systems exist today that are able to sense the aberrated wavefront and apply a conjugate-wavefront correction to the optical wavefront using adjustable-figure mirrors. The art/science of sensing and making this correction is known as *adaptive optics* (see Appendix A). The present state-of-the-art in adaptive optics is approximately 1000 Hz, which meets the requirements of some of the Atmospheric Propagation problems for optical propagation to/from a ground-based system irradiating/viewing celestial and in-earth-orbit objects. In order to time resolve the dynamics of Aero-Optical distortions, however, even for propagation through laboratory flows of less than 10 m/s, wavefront sensors of from several times to many orders of magnitude more rapid are required. As such, until very recently (see Appendix A) only an approximate first level understanding of the Aero-Optics problem has been available. Such understanding has been able to estimate the

level of optical degradation that is likely to be encountered by propagation through Aero-Optical flowfields. Very recent advances in instrumentation have provided an avalanche of new information about the Aero-Optics problem. Two instruments in particular are responsible for these breakthroughs, first is the one-dimensional Hartmann sensor developed by Neal with a demonstrated rate of wavefront constructions of 2.3 KHz (Ref. [1]); this instrument has been used extensively in ongoing work at the Phillips laboratory for investigating optical propagation through aberrating flows of up to 10 m/s (see Appendix A). The second instrument, the Small-Aperture Beam Technique (SABT), was developed in this grant research. The SABT makes use of the fact, noted above, that the aberrations in the wavefront have a convective velocity in the direction of the associated flowfield; wavefront constructions have been demonstrated in this research at rates up to 100 kHz (Ref. [2,3]). The realization that the convective velocity could reduce the number of sensors needed to study the dynamics of optical wavefronts was first advanced by Malley, et. al. (see Appendix A and Ref. [4]). During this research we matured this idea into the SABT wavefront sensor. Also during this research, the SABT has been applied to a 7 m/s heated jet facility constructed in the Aero-Optics Laboratory at Notre Dame as part of this research; and, it has been applied to the measurement to the dynamic wavefronts associate with optical propagation through a Mach 0.8 compressible shear layer at the Arnold Engineering Development Center (AEDC), showing the wide range of applicability of the instrument.

## D. New Levels of Understanding in Aero-Optics Directly Related to the Research

As referred to above, at the beginning of our grant, only an approximate level-one understanding of the Aero-Optics problem was available. Because of our computational work and our development of the SABT (Ref. [5]) and its application to the 2-D heated jet (Ref. [6]) and to the AEDC compressible shear layer (Ref. [3]), our understanding of the Aero-Optics problem has advanced to level three and level-four understanding looks possible in the not too distant future. Although not based entirely on our efforts, a great deal of this understanding has been a direct consequence of our work. Even at the first level, we now have a clear understanding of the proper fluid-mechanic data to be used in estimating the passive optical degradation (Ref. [7]). We also know the spatial and temporal frequencies of the dynamic optical distortions associated with propagation through not only relatively-benign laboratory flows, but also a near-flight-condition compressible shear layer (Refs. [3,6]). We have been able to collect instant-to-instant time series of the dynamically-aberrated wavefronts caused by these fields. As an inroad to a level four understanding of the Aero-Optics Problem associated with these flows, we have even examined the adaptive-optic design requirements to compensate for the aberrations (Refs. [8,9]). In fact, this grant has been more productive than we had imagined possible at its outset.

# II. Objectives and Approach of the Research

The objectives of our research were to study the time-resolved, dynamically-evolving aberrated near-field OPD's due to optical

propagation through variant-index turbulent flow fields. Specifically, we examined the OPD's associated with optical propagation through a two-dimensional, low-speed heated jet, and optical propagation through a Mach 0.8 free shear layer that simulates flow over a viewing aperture in the side of an airplane. These studies depended on the collection of time series of time-resolved OPD's. Once collected, the dynamics and character of the optical aberrations were related to the dynamics and character of the turbulent flowfield, and the OPD time series were used to study the far-field focus patterns using Fourier optics.

The approach was to first mature an idea, proposed by Malley [Ref. 1], for exploiting the convective nature of the wavefront aberrations to design and fabricate a new kind of high-bandwidth wavefront sensor capable of capturing time-resolved, full-aperture OPD's at up to 100 kHz. Since no other wavefront sensor existed capable of capture rates greater than approximately 2 kHz, this required that we develop a numerical simulation of a spatially- and time-evolving 2-D heated jet and use the simulation as a numerical platform for developing the wavefront sensor. Once developed, the new sensor was used to capture OPD's for optical propagation through a 2-D heated jet. A 2-D, heated-jet experimental facility was designed and constructed specifically for this fluid-optic interaction work. Additionally, the sensor was used to capture OPD's for optical propagation through a Mach 0.8 free shear layer made available at AEDC for this research.

## III. Results

The wavefront sensor was developed and is now referred to in the literature as the SABT (Small-Aperture-Beam Technique) sensor. The

theoretical basis for the instrument was documented in an *AIAA Journal* article (Ref. [5]). The key to being able to develop the SABT was the development of a numerical simulation tool that made use of point-vortex methods. This code is briefly mentioned in (Ref. [5]); however, the only complete description of the method is contained in a dissertation (Ref. [10]), which is available through the University of Notre Dame and a journal article is planned. A brief overview of the method and some of the bench marking are contained in Appendix B. The code was used to develop a method for determining the accuracy of applying the SABT to an experimental flowfield; this method is detailed in (Ref. [6]).

The SABT sensor allowed, for the first time, the collection and analysis of time-resolved dynamic wavefronts due to propagation through turbulent, optically-active air flows. As mentioned above, the optical activity was created by, in the first case by heating an air jet and, in the second case, propagating through a compressible (Mach 0.8) pressure- and temperature-matched shear layer. The results for propagation through the heated jet were documented in an *Applied Optics* article (Ref. [6]) and the results for propagation through the compressible shear layer were documented in an *AIAA Journal* article (Ref. [3]).

Finally, a Fourier Optics propagation code was developed to look at the far-field (focal plane) ramifications of the dynamically aberrated wavefronts due to propagation through the jet and shear layer. In particular, the code was used to study the passive far-field pattern to be able to compute directly the instantaneous and time averaged Strehl ratio (a measure of the system-performance degradation ramifications) rather than relying on the large-aperture approximation used almost exclusively in prior Aero-Optical research. Further, the code allowed for an extensive

study of the effect of various design parameters associated with adaptive-optic corrections to the aberrated wavefronts. These studies have been documented in an *Applied Optics* article (Ref. [9]).

## IV. Dissemination of Results

### A. Publications

This research has produced a PhD Dissertation (Ref. [10]), a Masters Thesis (Ref. [11]), eight meeting papers (Refs. [2,7,8,12,13,14,15,16]), and four journal articles (Refs. [3,5,6,9]).

### B. Air Force Laboratory Interactions, DoD Interactions and Technology Transfers

In addition to presentations made at AFOSR-sponsored meetings, the Principal Investigator made annual trips to the Air Force's Phillips Laboratory to meet with Laboratory personnel to transfer information, discuss progress and obtain input into the progressing work. Notre Dame also was asked by AEDC personnel and Phillips Laboratory personnel to collect wavefront data using the SABT for propagation through the compressible shear layer at AEDC. This data was presented to personnel at AEDC and at the Phillips Laboratory in addition to being documented in an AIAA meeting paper (Ref. [2])and an *AIAA Journal* article (Ref. [3]). It is our understanding that these wavefront data have been used by the ABL development office at the Phillips Laboratory as part of their selection process for the development of the ABL. Along with these data, one of the competing contractors for the ABL development program used a version of the SABT sensor to make preliminary measurements of Aero-Optic effects in wind-tunnel tests. Notre Dame is also taking part in Navy Aero-Optics

tests in a system development program being run at Calspan. This participation is a direct result of techniques developed in our research.

## V. Personnel Supported under this Effort

In addition to providing approximately one month of support each year to the principal investigator, Dr. Eric J. Jumper, a full-time Masters student, James M. Cicchiello, and a full-time PhD student, Ronald J. Hugo were supported through their respective Masters and PhD Degrees. Dr. Hugo was also supported for three months of post-doctoral work prior to his joining the Phillips Laboratory as an in-house researcher. During the last year of the Grant, Edward J. Fitzgerald, a new PhD student working in this area, was supported from June 1996 until the end of the grant in February 1997.

# A Appendix

This section will provide background information to the fluid-optic interaction problem. It will begin by classifying the two main types of fluid-optic interaction problems, and then discuss, in chronological order, the history of the fluid-optic interaction problem. The section will conclude by discussing the technology currently available for compensating for the wavefront aberrations induced by fluid-optic interactions.

### Classifying the Fluid-Optic Interaction Problem

Historically, fluid-optic interactions have been separated into two categories (Refs. [ 17]). The first category involves problems of light transmission through fluid layers where the layer thickness is typically much larger than the diameter of the beam, while the second category involves problems where the light transmits through fluid layers of depth smaller than the beam diameter. The most commonly encountered form of the first category is in the transmission of light through atmospheric turbulence.

These ideas can be demonstrated more clearly if we assume the following scale sizes: "viewing" aperture or beam diameter ($d$), path length through the turbulent region ($\delta^*$), and characteristic-turbulent-eddy size ($\Lambda$). Thus problems that fall into the first category (referred to as *Atmospheric Propagation*), where the beam diameter ($d$) is much smaller than the size of the correlated structures ($\Lambda$) in the aberrating fluid of depth $\delta^*$, are classified by

$$d \ll \Lambda \leq \delta^* \tag{1}$$

while problems in the second category (referred to as *Aero-Optics*), where the aberrating-fluid-layer thickness ($\delta^*$) is smaller than the diameter of the beam ($d$), can be described by

$$\Lambda \leq \delta^* \ll d \tag{2}$$

The proposed study is concerned with Aero-Optics-type problems; however, a great deal of experimental and theoretical work has been conducted for Atmospheric-Propagation-type problems with the results being directly applicable to Aero-Optics-type problems. Thus, in order to perform a comprehensive review of previous work, both categories will be discussed.

### Previous Investigations Quantifying Optical Wavefront Distortion

The study of fluid-optic interactions has been ongoing over the past 40 years, which can be roughly divided into two twenty-year periods. The first period (1950-1970) consisted of mostly *analytical investigations* which developed techniques for predicting optical degradation, while the second period (1970-present) consisted primarily of *experimental investigations* aimed at experimentally quantifying the optical degradation. The cause of these two distinct periods is twofold: i) the analytical techniques reached an impasse, namely that of predicting the temperature field for a turbulent flowfield, and ii) the experimental techniques have been aided with the arrival of relatively-new technology (efficient laser devices, microcomputers, etc.).

### The Early Years (1950-1970)

Some of the earliest studies were concerned with the transmission of radio waves through the earth's atmosphere. The original impetus to study the transmission of radio waves came after it was discovered that the measured signal strength beyond the horizon of a transmitter was much greater than that which would be predicted by diffraction of radio waves around the earth's surface. It was proposed by Booker and Gordon (Ref. [18]) that these observations could be attributed to scattering of the radio waves in the ionosphere (in the 80-90 km range) due to variations in the dielectric constant (caused by density fluctuations). The work of Reference [18] formulated the problem in terms of the scattering of electromagnetic radiation by turbulent atmospheric fluctuations. Booker and Gordon (Ref. [18]) produced an equation for estimating the time-averaged off-axis radiant flux (power) caused by scattering. The model characterized the atmospheric turbulence with isotropic density fluctuations having an exponentially-decaying autocorrelation function. Later work by Villars and Weisskopf (Ref. [19]) refined the Booker and Gordon model by computing the scattering cross section using a Kolmogoroff spectrum. Their work yielded two separate equations for the evaluation of the effects of scattering; the first applied to all eddies larger than those where viscous dissipation becomes important (inertial range), while the second applied to all eddies smaller than those in the inertial range - i.e., it applied to all eddies in which viscous dissipation turns kinetic energy into heat. It should be noted that the

work of both References [18, 19] assumed the single-scattering Born approximation, i.e., once the light was directed away from the beam path it could not be redirected back into the beam path by further scatterings.

Another early investigation, and probably the first true Aero-Optic study, was performed by Liepmann (Ref. [20]) in 1952. The purpose of the study was to quantify the amount of image blur and hence sensitivity loss incurred by a Schlieren system when viewing through a compressible-turbulent boundary layer. Liepmann's investigation applied perturbation techniques to the ray equation, allowing for an estimate of the deflection of a beam of light as it propagated through the boundary layer. Liepmann was forced to make certain assumptions about the flow due to little being "known about the conditions in the turbulent boundary layer at high speeds." He assumed that the turbulence was homogeneous and that the turbulence intensities in subsonic flow would be of similar magnitude to those in supersonic flow ($1 < M < 4$). Even with these restrictions his analysis was able to predict the root-mean-square beam deflection for a beam transmitting through a Mach 2 flow at standard atmospheric conditions. It should be noted that even though Liepmann's analysis involved a number of assumptions, the most-advanced statistical theories in fluid-optic interactions have not been able to advance much past the early work of Liepmann in 1952. In fact, the most-commonly-used theory for estimating optical degradation using fluid-mechanic measurements (cf. Ref. [21, 22, 23]) is identical to the results of Liepmann.

The theoretical investigations of References [18, 19, 20] were followed by an experimental investigation by Stine and Winovich (Ref. [24]) in 1956 where the optical transmission characteristics of compressible turbulent boundary layers were investigated for Mach numbers from 0.4 to 2.5. Stine and Winovich quantified the optical degradation by measuring the time-averaged intensity of light by a photomultiplier for the aberrating flow-on case and then non-dimensionalized this value by that of the non-aberrating flow-off case. Stine and Winovich also compared their experimental findings to those predicted by the scattering theories of Reference [18], for which they found reasonably-good agreement.

In 1964, Hufnagel and Stanley (Ref. [25]) solved for the time-averaged Modulation Transfer Function (MTF) for light propagation through atmospheric turbulence using the wave equation and the assumption of isotropic turbulence. The results of Hufnagel and Stanley demonstrated that the effects of atmospheric turbulence were to reduce the value of the MTF over all spatial frequencies, which they showed to agree with existing experimental data. (Note: For the interested reader, an excellent description of the MTF is given in References [26, 27].)

The effect of exposure time on the MTF was analytically investigated by Fried in 1966 (Ref. [28]). The results of Fried's calculations showed that the image quality and hence magnitude of the MTF could be improved over all frequencies if the exposure time was reduced. This result was explained by a time-varying wavefront tilt (an aberration consisting of a constant spatial slope on the optical wavefront) imparted onto the beam by turbulent structures. Fried stated that the wavefront tilt would displace the far-field image but it would not reduce image contrast. These ideas were supported by re-examining results from the investigation of Hufnagel and Stanley (Ref. [25]) where the predicted MTF was lower than that measured by experiment. Fried showed that the lower prediction by Hufnagel and Stanley could be explained by the fact that they were time averaging their MTF over a long time period in comparison to the shorter exposure times used in the experiment; the result of longer exposure times leading to a more degraded prediction of MTF due to the incorporation of wavefront tilt.

The far-field, on-axis intensity degradation for a beam of diameter $d$ traversing an optically-active fluid medium was computed by Sutton in 1969 (Ref. [21]). Sutton defined the far field as a distance greater than $k\Lambda^2$ beyond the aberrating medium, where $k$ is optical wavenumber ($2\pi/\lambda$) and $\Lambda$ is the turbulence integral scale. The turbulence was assumed to be homogeneous and isotropic and only the long-term time-averaged intensity profile was evaluated. The analysis techniques used by Sutton were identical to those used by Hufnagel and Stanley (Ref. [25]), the only difference being that Sutton applied the results to a problem of Aero-Optics. Sutton investigated the effects of varying $d/\Lambda$ ($\Lambda$=turbulence integral scale) and the extinction coefficient $\alpha$ (quantification of the amount of light scattered) on the far-field intensity pattern.

By the late 1960's much of the theory had been developed for the transmission of electromagnetic radiation through the atmosphere. The maturity of the field was reflected by the consolidation of the many research articles into a textbook by Tatarskii (Ref. [29]). It can be noted that analytical investigations for both Aero-Optics and Atmospheric Propagation type problems were limited by the same impasse, that being the prediction of the real-time temperature field in a turbulent flowfield. This impasse restricted all analytical investigations to the computation of time-averaged statistical values for quantifying the optical degradation.

### More Recent Attempts to Quantify the Optical Wavefront Distortion (1970-present)

With the invention of the laser in 1957, and with the later refinements in its design, came a large number of

new applications involving the transmission of light. The integration of laser devices into aircraft for purposes of transmitting out of or receiving by the aircraft led to a mini renaissance in the fluid-optic interaction problem; this resurgence resulted in the creation of a new research field, *Aero Optics*. Aero-Optics usually refers to the propagation of optical information through flowfields surrounding atmospheric flight vehicles, as mentioned earlier in this Appendix.

A great deal of the work performed since 1970 has involved the experimental quantification of optical degradation for Aero-Optics type problems. One of the first works in this area was performed by Kelsall in 1973 (Ref. [30, 31, 32]) where a Fast-Shearing Interferometer (FSI) was employed in the measurement of the Modulation Transfer Function (MTF) for both Atmospheric Propagation as well as Aero-Optic propagation. The FSI allows for the measurement of the MTF for either short (1 ms) or long ($\gg$ 1 s) time periods. It should be noted that even though the short exposure of 1 ms was a relatively quick measurement, it still involved large amounts of time averaging when applied to flows with sizeable convection velocities (aircraft boundary layers, for example). Kelsall's investigation consisted of quantifying the MTF for three different propagation scenarios; the first was for a horizontal 13.3 km atmospheric path in which the optical source and receiver were both on the ground, the second was for long atmospheric paths with celestial bodies providing light sources, and the third was for a 25 cm path through the boundary layer on the fuselage of a KC-135 aircraft (this measurement was actually a double-pass measurement with the beam reflecting off of a mirror mounted on an airfoil about 1 m from the fuselage). From these three tests, it was concluded that the boundary layer was primarily responsible for the degradation in optical transmission/receiving from the KC-135 aircraft.

In 1975 Gilbert (Ref. [33]) quantified the amount of optical distortion through the turbulent boundary layer ($\approx$ 5 cm in thickness) on a Lear jet. Gilbert used two different optical measurement techniques, one being the FSI and the other being a Line-Spread Measurement Device. The line-spread measurement device measured the *One-Dimensional Point Spread Function* (the far-field intensity as a function of one spatial coordinate) of a large-diameter beam. Gilbert double passed a large-diameter beam through the aircraft boundary layer by reflecting it off of a mirror mounted on an airfoil placed approximately 25 cm from the aircraft fuselage. Gilbert's investigation showed that the results of the line-spread measurement device were in good agreement with the results of the FSI.

An extensive series of tests to compare two different methods of quantifying optical degradation were conducted in 1977 by a group of researchers (Ref. [34, 35]). The investigation consisted of comparing the results of a FSI with those obtained from hot-wire anemometry techniques (involving both constant-temperature anemometry and constant-current anemometry). The hot-wire measurements consisted of measuring the covariance function of the density fluctuations as a function of position in a compressible-turbulent boundary layer. To accomplish this, the researchers placed a rake consisting of four constant-temperature/constant-current wire pairs separated by fixed distances into the flow and traversed the boundary layer in the direction of beam propagation (normal to the fuselage). Based on these four spatial measurements, it was concluded that the correlation function for density fluctuations was exponential, from which the optical degradation was evaluated using the Aero-Optic linking equation (Ref. [21, 22, 23, 8, 9]). It was concluded that the point fluid-mechanic measurements, when compared to the results of the fast-shear interferometer, produced similar time-averaged quantifications for the optical degradation. (Note: It should be mentioned that these results from the point fluid-mechanic measurements were reviewed recently by Reference [36] and found to underpredict the values from direct optical measurement techniques.)

An experimental measurement of the optical wavefront distortion was performed by Klein et al. in 1989 (Ref. [37]) for the transmission of light through an aerocurtain. The aerocurtain isolates gases with different index of refractions through which a beam must travel and operates between gases at the same pressure. In the case of Reference [37], the intended application of the aerocurtain is in the dome of an observatory housing a high-power laser. The main requirements of the aerocurtain are: i) to protect the high-power optics from dust accretion and ii) to maintain the dome temperature constant in order to avoid optical aberrations caused by thermal expansion and contraction of the optical components and temperature gradients within the dome. The source of index-of-refraction variations in the aerocurtain are the temperature gradients across the aerocurtain.

The measurement of optical wavefront distortion by Reference [37] was accomplished via three techniques: the first being pulsed-laser interferometry, the second being made using constant-current wire measurements, and the third using a novel beam-jitter technique. The third method, being closely related to the optical wavefront measurement technique developed in the first grant will be discussed in some detail in the following. The method consisted of measuring the off-axis position ($\epsilon$) of a small diameter ($\approx$ 1 mm) He-Ne laser beam. Knowing the distance from the edge of the aberrating flowfield to the detector ($L$), the off-axis angle $\theta$ of the beam was estimated (using a small-angle approximation) to be

$$\theta(t) = \frac{\epsilon(t)}{L} \tag{3}$$

Knowing that the off-axis angle of the beam was equal to the slope of the optical wavefront at the location of the beam, and using the mean velocity of the flow in the aerocurtain (determined via hot-wire measurements), the *rms* of the optical-wavefront distortion was computed via the following equation

$$OPD_{rms} = \sqrt{\overline{OPD(t)^2}} \tag{4}$$

where an overbar represents the average with respect to time and the value of $OPD(t)$ is given by (using only the AC component of $\theta_i$)

$$OPD(t) = \sum_{i=1}^{N} -\theta_i U_c \Delta t \tag{5}$$

where $\Delta t$ is the time between samples of the off-axis position of the beam ($\epsilon$) and $N$ represents the number of time samples taken over time $t$ (i.e., $t = N\Delta t$). It should be mentioned that Reference [37] did not go into the detail given above in explaining the beam-jitter technique. In fact, the reference explained the technique using only the following two sentences:

> *The autocollimator gave both the vertical and horizontal beam angular jitter. This is converted to an rms optical path difference.*

It is assumed that the description of the technique given above is the way that the authors of Reference [37] intended, and it has been given here in order to assist in conveying the utility of the technique to the reader. The optical degradation values measured by the pulsed interferometer and the beam-jitter technique were found to be in close agreement; however, the values measured by the constant-current wire technique were shown to be consistently lower (ranging from 32% to 48% lower) than the measurements from the other two techniques. The authors stated that the jitter method was versatile and much less expensive to measure than the other two techniques.

Like the work of Reference [37], Wissler and Roshko (Ref. [16, 17]) also measured the deflection signal of a small-diameter He-Ne laser beam transmitting through a mixing layer. Although the work of Wissler and Roshko did not directly quantify the optical degradation, it was the first paper to investigate optical transmission in a non-statistical manner by linking specific flowfield events (large-scale-coherent structures) to specific beam-deflection patterns. Index-of-refraction variations were created by the mixing of two dissimilar gases, one case used a mixture of $He/N_2$ and another used a mixture of $N_2/He - Ar$. Beam deflections in the streamwise direction were found to be caused by spanwise coherent structures, while deflections in the spanwise direction were found to be caused by streamwise vortical structures. The streamwise deflection was found to be greatest at the trailing edge of the spanwise coherent structures, while the spanwise deflections were found to exhibit large variations across the span of the flow. The *rms* fluctuations of the streamwise and spanwise beam positions, when plotted as a function of downstream location, were found to peak at the location of mixing transition. The mixing-transition point was defined as the location where the flow becomes predominantly three-dimensional, which implies a large increase in the interfacial area between the two fluids.

A series of three papers investigating the propagation of light through a free shear layer was performed by a group at the University of Washington (Ref. [38, 39, 40]). The first paper (Ref. [38]) numerically investigated the effects of forcing on the shear-layer growth rate and its consequences in terms of optical transmission. The simulation was performed using the two-dimensional Euler equations which were solved using the second-order, explicit, MacCormack predictor-corrector and Godunov methods alternately. The simulation provided the instantaneous density field, from which the optical phase front was computed as a function of time and streamwise location. Knowing the near-field optical phase front, the far-field intensity pattern was computed for a round aperture. The Strehl ratio, which is defined as

$$SR = \frac{I}{I_o} \tag{6}$$

where $I$ is the maximum light intensity in the far-field pattern for an aberrated system divided by $I_o$, the maximum light intensity in the far-field pattern for the same optical system without aberrations (diffraction limited far-field

intensity pattern), was then evaluated as a function of time. It was found that $SR$ was the smallest (most degradation) at the trailing edge of the coherent structures. This result was attributed to the high density gradients present in the streamwise direction with the passage of one of these structures, consequently resulting in large phase-front distortions and large aberrations. The forcing of the shear layer at both the fundamental frequency and the first subharmonic was investigated and it was found that, in the non-growing region of the shear layer, the fundamental frequency resulted in the least optical degradation (based on the time-averaged $SR$). This was explained by reasoning that the fundamental forcing prevented structure amalgamations from occurring and hence "locked" the coherent structures into their smallest possible size, resulting in the smallest phase aberrations and consequently the best transmission conditions.

The second and third papers from the University of Washington group (Ref. [39, 40]) experimentally investigated the far-field intensity pattern produced when a beam was transmitted through the shear layer. The far-field intensity was measured with a CCD camera capable of taking snapshots of the flow with a shutter speed of 10 kHz ($100\mu s$ exposure time) or taking long exposure far-field intensity patterns (2 s exposure time). The second paper (Ref. [39]) served to verify the numerical-simulation results of the first paper (Ref. [38]) by first proving that large-scale coherent structures did, in fact, effect the optical-transmission characteristics; and secondly, that forcing the shear layer at its fundamental frequency did, in fact, reduce the amount of optical degradation, in the mean, over that for the unperturbed case. The third paper (Ref. [40]) investigated the relationship between the shear-layer fluid mechanics and beam-propagation quality. It was found that the time-averaged $SR$ was more or less constant prior to the onset of mixing transition, decreased with downstream position in the transition region, and then finally reached an asymptotic value in the post-transition region. The asymptotic behavior of the $SR$ in the post-transition region was explained as being a consequence of the increased mixing within the large coherent structures, which then resulted in a uniform field inside the cores of the vortices, resulting in a reduction in phase distortion.

A recent investigation (1993) by a group at Sandia Labs (Ref. [12]) has developed a high-speed (2.3 kHz) one-dimensional Hartmann wavefront sensor. The device uses a line-scan camera and provides a cross-section of the optical wavefront as a function of one spatial dimension and time. The researchers applied the device to three different flowfields: a volumetrically heated gas, grid turbulence, and droplet evaporation.

Two papers (Refs. [53, 54]) by a group of researchers at the USAF Phillips Lab have applied the Linear Array Dynamic Wavefront Sensor developed in Reference [12] to study the fluid mechanics of a heated axisymmetric jet. The first of the two papers (Ref. [53]) discusses the application of wavefronts measured by the one-dimensional Hartmann sensor to tomographical analysis techniques with the goal being the quantification of the flowfields time-dependent density field. In performing this investigation, the one-dimensional wavefront was sampled at 2.2 kHz using 40 sub-apertures with a total aperture size of 2.5 nozzle diameters (2.54 cm). The second paper (Ref. [54]) used the same one-dimensional Hartmann sensor (only now with a smaller total aperture size of 1 nozzle diameter) to quantify the linear amplification rate of disturbances in the jet's shear layer.

Reference [41] presented design aspects for an innovative method of obtaining optical-wavefront information from holographic-particle-image velocimetry measurements in a compressible free shear layer facility. The basis of the technique involved measuring the velocity field using particle-image velocimetry and then relating the measured velocity field to the density field through the isentropic relationship. The high-speed layer in the compressible free shear layer facility was moving at 270 m/s while the low-speed layer was moving at 30 m/s, from which the investigators estimated that the temporal frequencies in the distorted optical wavefront would be on the order of 20 kHz.

## Adaptive Optics for Correcting Optical Wavefront Distortions

Adaptive-optical corrections involve *the control of a beam of light in a real-time closed-loop fashion* (Ref. [55]), where control refers to the conditioning (or modification) of the optical wavefront. Conditioning can be performed in two different ways: one involving conditioning in such a way as to remove the wavefront distortion from light that has already traveled through an aberrating medium (an example being astronomical observations or the *receiving scenario*) while the second conditioning method involves the superposition of an intentional distortion onto an optical wavefront that is about to transmit through an aberrating medium in such a manner so that the wavefront emerges from the aberrating medium without distortion (an example being energy transmission or the *transmitting scenario*). Adaptive-optical systems, due to their closed-loop nature, consist of both **sensing** the optical wavefront distortion through *optical-wavefront sensors* and applying **correction** to the optical wavefront through *deformable mirrors.*

The interest in applying adaptive optics to Aero-Optical flowfields comes as a result of the recent successes in the application of adaptive optics to the correction of atmospheric turbulence in ground-based astronomy (Refs. [56, 57]).

These corrections are applied to telescopes several meters in diameter at frequencies of several hundred hertz, and due to the relatively-large spatial scale of the atmospheric distortions, the optical wavefront need only be sampled at spatial frequencies on the order of every 10 cm (Refs. [57, 28]). The scenario for the Aero-Optical flowfield is, however, quite different due to the relatively large convection velocities ($\approx$ 300m/s) and the relatively small aberrating-structure size (several orders of magnitude smaller than the aberrating-layer's thickness). As a result, the temporal frequencies of the distortion in the optical wavefront have been estimated to be on the order of 20 kHz (Ref. [41]) and the spatial scale of the distortion estimated to be on the order of millimeters. As such, the application of adaptive-optics technology, originally designed for flowfields with temporal frequencies on the order of a few-hundred hertz, to flowfields with temporal frequencies two orders of magnitude larger, requires the development of new technology.

As mentioned earlier, adaptive-optics consists of two main parts; the first being the sensing of the optical wavefront distortion by way of an optical-wavefront sensor, and the second being the correction of the optical wavefront through a deformable mirror. The frequency bandwidths of these two main components are, however, quite different, with the current *state-of-the-art* **real-time** optical wavefront sensors operating at approximately 300 Hz (Ref. [58]) and the current generation of deformable mirrors operating at approximately 500 kHz (Ref. [57]). As a consequence of this large difference in frequency bandwidths, the optical-wavefront sensor is seen to pose the greatest restriction in the application of adaptive optics to Aero-Optical flowfields, where temporal frequencies are on the order of 20 kHz.

# B Appendix

This section provides a brief discussion of the numerical simulation developed as part of this research. As mentioned in the main body of this report, the details of how the SABT Wavefront sensor works is contained in Ref. 5; however, it suffices to say here that the high bandwidth (100 kHz plus) is realized by the fact that it is a sparse instrument. The sparseness is achieved by reducing the number of subapertures (in the Hartmann-sensor sense) or probe beams in the streamwise direction by invoking a Taylor's frozen-flow approximation. The fact that the flow evolves means that the frozen flow approximation does not strictly hold. It is the deterioration of the frozen-flow approximation with subapertures/probe beam separation that reduces the accuracy of the sensor. Since no other sensor was available to us to develop the algorithms and accuracy of our newly developed sensor, we had to devise a scheme to accomplish these ends. The approach we choose was to develop a discrete vortex method (DVM) code to simulate an unsteady, optically-active flow field through which a numerical version of our sensor could be studied. These numerical simulations formed the basis of the development of the sensor [Ref. 5], and the method of estimating the measurement error when experimentally applying the sensor [Ref. 6]. Figure B.1. shows a time series of the dynamic optical wavefronts aberrated by propagation through a two-dimensional heated jet produced by the simulation. Although the requirement of the code was only to produce an optically-active flow field that both convected and evolved, it can be noticed from the instantaneous snap shot of the edges of the jet shown in the Fig. B.1. (labeled "Aberrating Flowfield"), that the code produces a flow that is at least similar to flow visualization images of a two-dimensional jet. Further, actual experimental wavefront measurements made for optical propagation through the heated two-dimensional jet, like the time series shown in Fig. B.2., show a similar nature to the numerically-simulated time series in Fig. B.1. A more detailed study of the code and comparisons to other shear-layer simulations showed that the code did an excellent job of simulating the early Kelvin-Helmholtz driven, two-dimensional roll up.

### Method Description

The numerical simulation made use of a single-layer discrete-vortex method, similar to that originally used by Rosenhead [Ref. 59]. The method differs from that of Rosenhead in a number of ways: the number of vortices used is much greater, and thus the vortices are more closely spaced; the vortices have finite cores; and the center of each vortex is always less than a core radius from its adjacent vortices. In order to maintain this last stipulation, the code adds (inserts) vortices as it runs. Other researchers [Ref. 60, for example] have discretized the shear layer by using multiple layers; however, advantages gained by multiple layers come at the cost of an increase in the computational demands needed for the simulation. Because of our requirement to run the simulation on a workstation environment, we choose to use only a single layer. The insertion method used in our code is similar to that by Ghoniem, et. al. [Ref. 60]; however, the method used in our code is both simpler (mainly because of the single layer) than that of Ref. [60] and rationally based. Insertion of a new vortex is made when the distance between adjacent vortices becomes equal to the core radius, then a new vortex is inserted half way between these adjacent vortices and the strength of the vortex is set equal to one third the sum of the original adjacent vortices' strengths and the adjacent vortices' strengths

reduced appropriately. When these conditions are met, the circulation is preserved and the stability remains unchanged.

### Comparisons: Temporal Development

The code was configured to model the temporal evolution of an inviscid, spatially-periodic, infinite shear layer. Following Ref. [60], each of the discrete vortices in the spatially-periodic shear layer was modeled using the velocity field given by Lamb [Ref. 61] for the induced flow field due to an infinite row of equidistant vortices. The shear layer at time zero was modeled by considering only a single cycle of an infinite shear layer, the one cycle being approximated by a finite number of vortices which extend over one wavelength of the cycle. The core size of the single-layer shear layer was matched in a least-squared sense to the eleven-layer, error-function velocity profile through the layer given by Ref. [60] (see Fig. B.3.). The growth rate of the shear layer was quantified in an integral sense following Ref. [60], and tracked as a function of non-dimensional time for each of several disturbance amplitudes, examples of which are shown in Fig. B.4. The characteristics of the curves were similar to those noted by Ref. [60]. From these data the growth rate was computed. For the curves shown in Fig. B.4., these rates were found to be 0.21, 0.18 and 0.22 for the disturbances from smallest to largest, respectively. Linearized small perturbation theory predicts a growth rate of 0.22. Similar results from Ref. [60] gave 0.21 to 0.24. As with Ref. [60], single cycles were connected at various times associated with a "convection time" and plotted to represent a "pseudo-spatial" development of a shear layer and this compared to an experimental shear layer by Roberts, et. al. [Ref. 62]; a comparison is shown in Fig. B.5. We conclude from these and other comparisons that, while we acknowledge that some advantage may be gained by using multiple-layer simulations, our single-layer method is comparable to the multiple layer methods in terms of preserving the definition of the shear layer, its evolution and its stability characteristics.

### Spatially-Developing Layer

The general scheme for proceeding with a simulation for a two-dimensional jet is shown in Fig. B.6. This scheme is similar to the simulation of an axisymmetric jet by Acton [Ref. 63]. After Ashurst [Ref. 64], the growth of the instabilities in the jet can be tempered by allowing the vortex cores to grow. In Ashhurst's case, the cores were allowed to grow with time at the rate for a single vortex found from an exact solution of the Navier-Stokes equations. In our case, when this rate was used in the code, the momentum thickness of our layers grew more rapidly than we experienced in our experimental jet. By performing numerical experiments, we were able to find a growth rate that produced flowfields similar to those of the experiment; however, the rate did not appear to be justifiable from single-vortex theory. The fundamental difference between our method and that of Ref. [64] was our use of vortex insertion. When using insertion (which always guarantees closely-space discrete vortices), rather than the vortex cores growing at a rate compatible to that of a single free vortex, the growth of the cores should be more closely modeled by the laminar momentum diffusion of a parallel shear layer. When the rate given by the exact Navier-Stokes solution of a parallel laminar shear layer [Ref. 65] was used, it was found to closely match the rate that we had determined to be appropriate from our numerical experiments.

## Numerical Optics

In our simulation the temperature of the jet is higher than that of the surrounding fluid. With the vortex insertion method, the definition of the shear layer is well defined and the temperature difference is maintained across it. Normally, in a gradient-index field the ray-tracing equation is used to compute the trajectory of a small-aperture beam of light. In the limit of a discontinuity in temperature across a layer, the index gradient is infinite and Snell's law replaces the ray-tracing equation. In either a gradient-index case or the Snell's-law limit, the ray may experience total internal reflection, the Brewster angle in the Snell's-law limit. In the case of our simulation, this limit was experienced often, as the layers folded upon themselves with the development of organized structures in the flow (see Fig. B.1.). This caused scintillations for a spatially-fixed probe beam propagating normal to the flow, or convecting streaks void of light that appeared to convect with the flow in the case of a sheet of light directed normal to the flow. In order to provide a continuous signal and to account for thermal diffusion across the shear layer a scheme was devised that took advantage of Huygen's Principle. The local emerging wavefront slope was determined by integrating the optical pathlength through the jet at two locations a small distance apart. Then, by Huygen's principle the off-axis probe-beam angle could be computed by dividing the difference in the optical pathlength by the small distance between locations. Even this method could produce large spikes in the beam jitter depending on the distance between locations. To soften these abrupt angle deflections experimental beam diameter distances were used and any particular-location's optical pathlength was determined by averaging the optical pathlengths over some distance (smaller than the probe-beam diameter) on either side of that location. This averaging distance, which resulted in softening the OPD, was allowed to increase with position from the jet nozzle exit to simulate thermal diffusion.

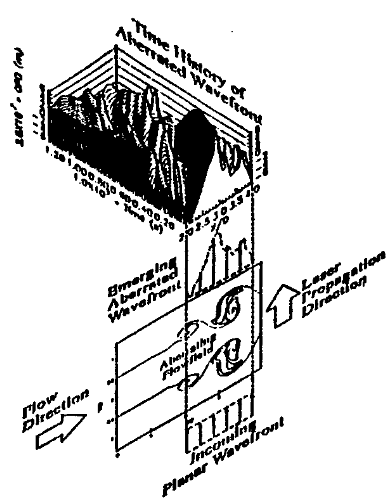


Figure B.1. Numerically-Computed Flowfield and Time-Varying Aberrated Wavefront.

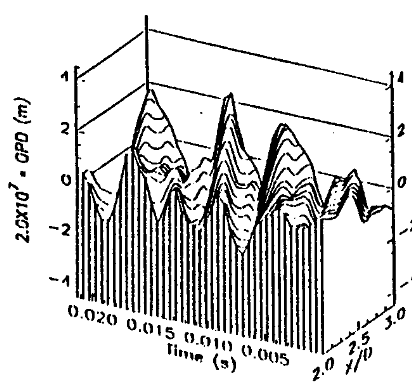


Figure B.2. Time Series of Experimental Wavefronts from Heated Jet.

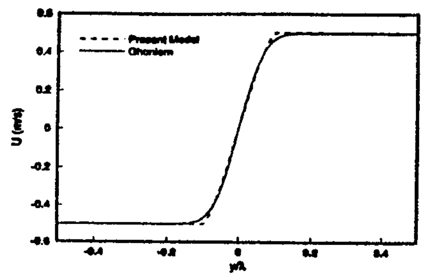

Figure B.3. Mean Velocity Profile

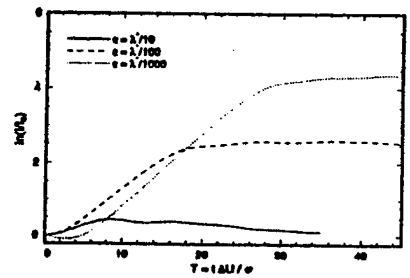

Figure B.4. Growth of Perturbation

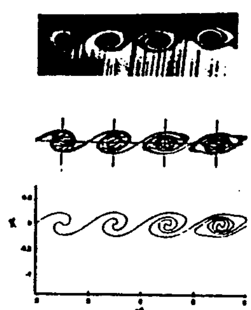

Figure B.5. Pseudo-Spatial Development of Shear Layer: Top - Roberts; Middle - Ghoniem; Bottom - Present Method.

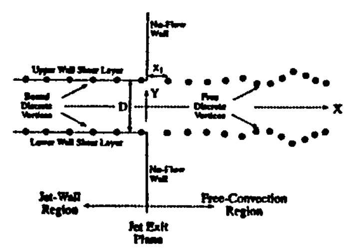


Figure B.6. Discrete Vortex Representation of Shear Layer

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